THE INTERNATIONALIZATION OF AGRICULTURAL TECHNOLOGY: PATENTS, R&D SPILLOVERS, AND THEIR EFFECTS ON PRODUCTIVITY IN THE EUROPEAN UNION AND UNITED STATES

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Multilateral indices of total factor productivity (TFP) allow efficiency comparisons between ten European Union countries and the United States from 1973 to 1993. Differences in TFP levels are then explained by land quality differences, public research and development (R&D) expenditures, education levels, private-sector patents, international spillovers of public R&D, and private-sector technology transfer. There is evidence that public R&D results in limited knowledge spillovers between the European countries and the United States. However, the use of international patent data from the Yale Technology Concordance shows not only that patents matter, but also that private sector technology transfer may be the dominant force in explaining TFP trends. The United States and the European Union countries with more advanced research systems (Netherlands, Denmark, France, and Belgium) converge in a high-growth club, while Germany, Luxembourg, Greece, Italy, Ireland, and the United Kingdom form the slow-growth group. Ignoring knowledge spillovers and technology transfer leads to biased estimates of R&D elasticities, which is hardly surprising since the private sector is now spending more than the public in some of these countries. Thus, the estimated rate of return to public agricultural R&D falls from over 60% in the closed economy model to 10% in the model that takes account of international spillovers. (*JEL* Q16)

I. INTRODUCTION

The pioneering work of Jorgenson and Nishimizu (1978), on intercountry comparisons of total factor productivity (TFP), has led to a literature on multilateral TFP indices, which allow competitiveness to be measured both intertemporally and interspatially. The theoretical issues are discussed in Caves et al. (1982) and applied to agriculture by Capalbo et al. (1990, 1991). Empirical work on European Union agriculture can be found in Terluin (1990), Bureau et al. (1992) and Ball et al. (1996), updated versions of whose indices are used in this study.

Evenson et al. (1987) show that changes in agricultural TFP can be explained by means of "determining" variables, such as R&D, extension, and farmer education. They call this approach to explaining technical change the "two-stage decomposition," as opposed to the "integrated" approach, in which the "determining" variables are incorporated directly in the estimation of the production, cost, or profit function. Both approaches are common in the

*Previous versions of this paper have been presented at the Western Economic Association International 72nd Annual Conference, Seattle, Wash., July 12, 1997 (session organized by Caswell and Schimmelpfennig); the 1997 Economic Research Service and Farm Foundation sponsored workshop on "Public-Private Collaboration in Agricultural Research"; the 1998 annual meeting of the ASSA in Chicago; the 1998 NC208/CIMMYT conference at El Batan, Mexico; and the 1998 annual conference of the Agricultural Economics Society at Reading, England. We thank Eldon Ball of the USDA for the TFP data, Robert Evenson of Yale University, and Daniel Johnson of Wellesley College for the patent variables, and Han Roseboom of ISNAR for providing research expenditure data. We thank Daniel Johnson, Walter Park, and all the participants for helpful comments, and especially Robert Evenson, who influenced the final form of the paper. David Hadley of University of Reading, Rob Townsend of the World Bank, and Ellen Bielema and Charlie Hallahan at USDA provided excellent econometric assistance. The views expressed are not necessarily those of the USDA.

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Contemporary Economic Policy
(ISSN 1074-3529)
Vol. 17, No. 4, October 1999, 457–468

considerable literature on the returns to agricultural R&D surveyed by Echeverria (1990). However, previous estimates of the returns to R&D for European agriculture (see Rutten, 1992; Thirtle and Bottomley; 1989, Khatri and Thirtle, 1996) fail to allow for spillovers between research jurisdictions, due to lack of data. Evenson and colleagues (Evenson and Pray, 1991; Huffman and Evenson, 1993) have shown that spillovers can be important.

Indeed, endogenous growth theory rests on the notion of positive spillovers, resulting from the nonrivalness of new technology, combined with the inability of firms to appropriate fully the returns to their research investments, which results in increasing returns at the aggregate level. Thus, technological spillovers form the basis of the increasing returns in Romer's (1986, 1990) models, just as they provide the rationale for public investment in agricultural research. Lucas (1988) introduces increasing returns in the aggregate production function by allowing individual human capital investments to have positive spillovers on the productivity of the human capital investments of others. In both the Romer (1986) and Lucas (1988) models, policies that impede investment in human and physical capital reduce growth, and appropriate public policies accelerate growth.

The particular policy focus of this paper is the U.S. Department of Agriculture's (USDA) concern with effective coordination of public and private research in the United States (Fuglie and Schimmelpfennig, 1999). For this purpose, private as well as public R&D must be considered in the global environment of the multinationals, which have played a major role in internationalizing agricultural R&D. Agricultural productivity in one country might depend on its own research efforts and the level of the pool of international knowledge that it has access to, so modeling international spillovers is essential.

The United States and the European Community (EC) countries with more advanced research systems (Netherlands, Denmark, France, and Belgium) form a high-growth club, probably due to technological and geographical proximity, in which international spillovers are a powerful force, and there is conditional β convergence in their levels of TFP. Germany, Luxembourg, Greece, Italy, the United Kingdom, and Ireland form a slow-growth group. The United Kingdom is the exception, in that its international connections should put it in the high-technology set, but it has fallen into the low-growth club since the reductions in public R&D in the 1980s. Schimmelpfennig and Thirtle (1999) suggest that public international spillovers are partly responsible for the divergence between these two clubs, through either external increasing returns or technical change.

The next section of this paper compares the multilateral agricultural TFP indices for the 10 EC countries and the United States. Then, section III explains why the model has to allow for spillovers between the public national agricultural research systems (NARs) in the EC, for intercontinental spill-ins from the U.S. system, and also from private sector research activities. Section IV covers the model and the data, including the manipulations and lag structures required. Section V, establishes the importance of spillovers, using a panel data model. In section, VI marginal internal rates of return to public agricultural R&D are calculated for the different models, and section VII offers conclusions.

ABBREVIATIONS

AIC: Akaike Information Criteria
LSDV: Least squares with country-specific dummy variables
MIRR: Marginal internal rate of return
NARs: National agricultural research systems
OECD: Organization for Economic Cooperation and Development
PDL: Polynomially distributed lag
PIM: Perpetual inventory model
PPPL Purchasing power parity
R&D: Research and development
SC: Schwartz Criteria
TFP: Total factor productivity

II. MULTILATERAL PRODUCTIVITY COMPARISONS

Bureau et al. (1992) constructed Fisher TFP indices for 10 EC countries and the United States, for 1973–1989. Then, to allow international comparisons, agricultural sector purchasing power parity (PPP) exchange rates were calculated to make the outputs and inputs of the 11 countries comparable. The spatial index, for 1985, was used to calibrate the time series for each country, giving multilateral indices. This work has been updated by Ball et al. (1996), whose results are summarized in Table 1.

TABLE 1

TFP Comparisons for 10 European Community Countries and the United States, 1973–1993

BELG	DENM	IREL	FRAN	GERM	GREC	ITAL	LUX	NETH	UK	USA	EC10
Starting level, 1973–1975 average (base is EC10 = 100 in 1990)											
117.3	91.1	54.9	78.6	63.0	59.0	63.4	30.0	101.7	80.3	93.7	72.3
Final level, 1991–1993 average (base is EC10 = 100 in 1990)											
147.4	138.1	77.3	128.7	87.3	77.7	93.6	37.2	139.7	105.3	156.9	106.0
Growth rates, 1973–1993											
1.3	2.6	1.9	3.0	1.9	1.5	2.2	1.4	1.8	1.6	3.0	1.92

Ball et al. (1996) show that in 1973 the United States was more efficient than all the European countries, except for Belgium and the Netherlands. However, there are considerable annual variations, so it is better to base the comparison on an average. Thus, the first row of Table 1 shows the efficiencies of the EC countries and the United States, relative to the aggregate of the EC countries, averaged over 1973-1975. On this basis, the Netherlands and Belgium did perform better than the United States, but Italy, Germany, and Greece were at less than 70% of the U.S. efficiency level, and Luxembourg was at less than one third of the U.S. productivity level. Using an unweighted average, the EC countries achieved 77% of the U.S. efficiency level.[1]

The growth rates shown in the last row indicate that only France has grown as fast as the United States, with Denmark not far behind, while all the rest of the EC countries have fared considerably worse. Thus, as the spatial index in the penultimate row shows, by 1991-1993, the United States had overtaken the Netherlands and Belgium, which both grew slowly; the French remain just as far behind the United States and all the other countries had fallen still further behind. Since the growth rate of the 10 EC countries in aggregate was only 1.9%, they are at only 67% of the U.S. efficiency level at the end of the period.

These data allow a test of simple versions of the convergence hypothesis. Dowrick and Nguyen (1989) found that for the Organization for Economic Cooperation and Development (OECD) countries since 1950, "TFP catch-up stands out as a dominant and stable trend." For their sample, initial levels of income were negatively related to growth rates and accounted for over 50% of the variance. Thus, the richer countries grew more slowly, and there is a tendency for income levels to converge. This does not seem to be suggested by the data in Table 1. Indeed, regressing the TFP growth rates on the starting values shows that there is no clear relationship, since the estimated coefficient is not significantly different from zero.

However, when we turn to explaining interspatial and intertemporal efficiency differences, adding the starting points to the other explanatory variables shows that they are significant in explaining the variation. Quah (1997) considers the possibility that countries of close technological proximity will form convergence clubs, whereas those who are more technologically backward may fail to keep up. This more interesting case is supported by Figure 1, which shows the TFP indices for all the countries. A high-technology club, comprising the United States, France, the Netherlands, Belgium, Denmark, and the United Kingdom appears at the top of the figure. These first five follow convergent paths with high levels of TFP. The United Kingdom appears to be a member of the group until 1984 and then is left far behind as its growth rate fell considerably. It is not coincidental that U.K. public sector R&D on agricultural research peaked in 1983 and by 1989 was 12.5% lower (Thirtle et al., 1997).

The United Kingdom joins the low TFP level club by 1993. The countries in this group have less technologically advanced research systems, and the technological distance from the leaders may be proving too great for them to stay in touch with the leading group. Their average growth rate is 1.5% per annum as compared with 1.75% for the leading group, so if they converge it will be to a lower TFP level.

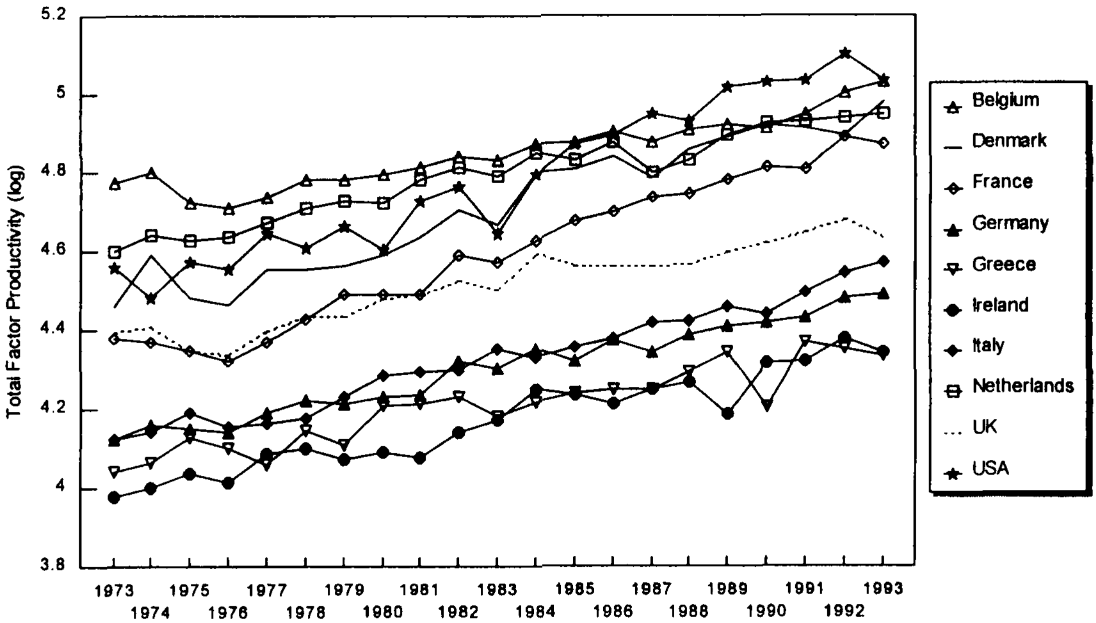
We now continue by explaining the variation in TFP, with public and private R&D, international spillovers, education, and land quality. The importance of spillovers suggests that there is an R&D hierarchy, with a leading group in touch with the international system and a trailing group for whom the technological distance is too great. Thus, spillovers partially explain why there are two TFP growth clubs.

III. EXPLAINING TFP GROWTH

Using the "two-stage decomposition" approach described in section I, changes in TFP indices can be explained by "conditioning" factors that shift the static production function over time. In the basic closed economy model these are public sector R&D expenditures that generate new technology, a land-quality adjustment, and the education level of the farmers, which affects both their own creative and managerial abilities and their skill in apprais-

1. Note that an average with weights to reflect output shares would be considerably higher. As it is, Luxembourg, which has a really tiny agricultural sector, carries the same weight as France and Germany.

FIGURE 1
High- and Low-Level Agricultural Productivity Clubs



ing and adapting exogenous technologies.[2] This study incorporates domestic patents to capture the effects of private sector R&D. Knowledge spillovers between the EC countries and from the United States are captured by including the effects of foreign public R&D, and private sector technology transfer is modeled using international patent data.

Conceptually, considering the EC countries as a group is similar to working with data for the United States as a whole rather than handling the states individually, since there are considerable spillovers of research benefits between the state jurisdictions (Evenson, 1989; Huffman and Evenson, 1993). Thus, technological spillovers between the EC countries should be incorporated. Like Lichtenberg and de la Potterie (1996), Coe and Helpman (1995), and Park (1995), who aggregate foreign R&D into one variable, we estimate a panel data model with foreign R&D as one variable.

Including the United States allows for the possibility of intercontinental spillovers. Technical change in the input industries should be captured in the input series, but these are unlikely to account fully for quality changes (Cooper et al., 1993), so private sector activity is measured by international patent data. The counts of patents pertaining to agriculture, registered by country i in country j, provides country-specific information on foreign private technology transfer between the 10 countries.[3]

These private sector variables and international public spending effects are all required to prevent misspecification. To avoid omitted variables bias, adequate variables have to be found to capture all these effects. Thirtle et al. (1995) used lagged foreign TFP indices as proxy variables for foreign private activities as well as public research, with some success. However, the lagged TFPs incorporate all the spillovers, which introduces simultaneity problems, and private domestic R&D is still not accounted for. The approach taken here is preferable since it takes account of public and

2. Weather variables and extension expenditures that transmit research results to farmers, thus diffusing technology, have been used in the extensive literature in this area, but were not jointly significant with the other variables here. Since extension has been wholly or partially privatized in several of the countries, there are missing data and those available have very little explanatory power.

3. The relationships among R&D expenditures, patents and innovations are covered in Johnson and Evenson (1997).

private domestic R&D and public and private spillovers from other countries without using the TFPs as proxy variables for technology. The international patent flows, like those shown in Evenson and Johnson (1999) are used to capture the effects of private domestic R&D and international spillovers of private technology, at a country-specific level. Thus, the results reported here are from a panel model like that of equation (5) in Evenson and Johnson, but fitted to the 10 countries shown in our Table 1 (Luxembourg is omitted).

IV. THE MODEL, THE DATA, TRANSFORMATIONS AND LAGS

The TFP indices that are the dependent variables in equation (1) below were discussed in section III. Explanatory variables, for the same countries, are available for 1963–1993 and begin with public R&D expenditures, measured in constant 1980 PPP U.S. dollars and updated from Pardey and Roseboom (1989). The international patent data, from the Yale Technology Concordance, are the number of patents pertaining to agriculture, registered by the country of origin in the country of use. Education is an annual index of years of secondary education, constructed from various issues of the World Bank World Tables, and the land quality variable is from Peterson (1987). All the variables except the land quality index have lagged effects on TFP, so the model is

$$(1) \quad TFP_t = \sum_{l=1}^{L_1} \alpha_l RD^d_{t-l} + \sum_{l=1}^{L_2} \beta_l RD^f_{t-l} + \sum_{l=1}^{L_3} \gamma_l PAT^d_{t-l} + \sum_{l=1}^{L_4} \delta_l PAT^f_{t-l} + \sum_{l=1}^{L_3} \sum_{m=1}^{L_4} \eta_{lm} PAT^d_{t-l} PAT^f_{t-m} + \sum_{l=1}^{L_5} \mu_l E_{t-l} + \varphi LQ_t + \theta SV_t + u_t,$$

where $t = 1$, T and the TFP index at time t is a function of its own R&D expenditures (RD^d), lagged from one to L_1 periods, and of RD^f for all the other nine countries, lagged from one to L_2 periods; of own-country patents (PAT^d), lagged from one to L_3 periods, and patents registered by all other countries (PAT^f), lagged from one to L_4 periods; and the interaction of own-country patents with patents registered by all other countries. E = education, LQ = land quality, and SV = the initial level of TFP. Lastly, u_t is a stochastic error term. All the variables are logarithms, and all but the land quality index are weakly exogenous because they are lagged and therefore predetermined. The sample is reduced to 10 countries because Luxembourg is excluded, due to lack of data.

There are several alternatives for modeling the lagged variables, but including up to 10 lagged values of own-country R&D and foreign-country R&D, plus lags for education and patents, is not feasible, due to lack of degrees of freedom and collinearity. Instead of including all the lagged variables as in equation (1), lag structures are imposed, and the National Agricultural Research System (NARS) R&D is modeled either by using the perpetual inventory model (PIM) to form knowledge stocks, or by imposing second-degree polynomially distributed lag (PDL) structures (inverted U-shapes), which is a common approach (White and Havlicek, 1982; Thirtle and Bottomley, 1989). The PIM knowledge stocks are calculated before taking logs, using the well-known formula

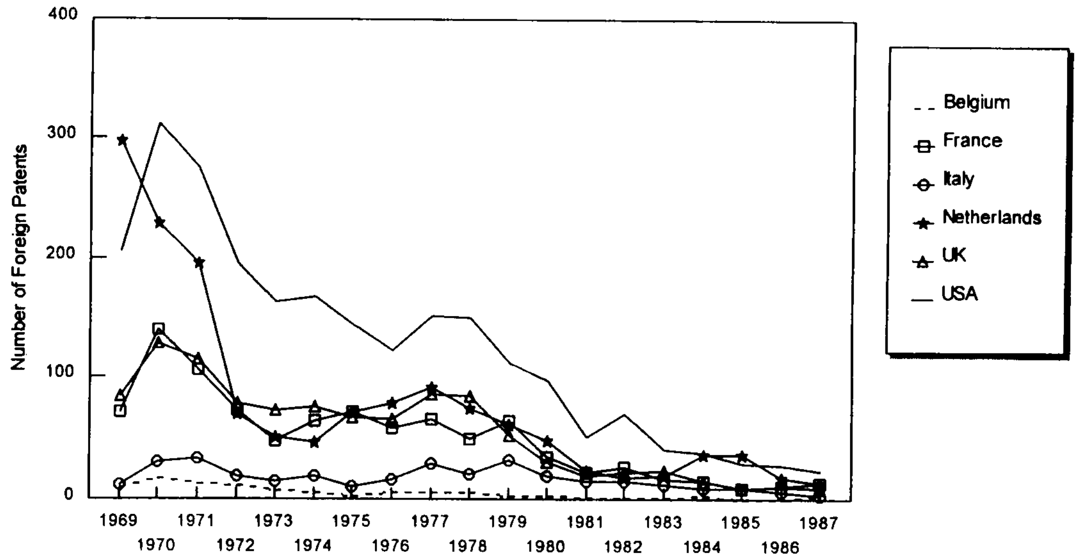
$$(2) \quad K_t = (1 - \delta)K_{t-1} + RD_t,$$

where K_t is the knowledge stock at time t, which is the stock at $t - 1$, plus the R&D expenditures in year t. Delta (δ) is the rate of depreciation, which was set at 5%, since the effects of R&D are expected to persist for up to 20 years. Then, the PIM knowledge stock is lagged 7 years to allow for the gestation period from expenditures to effects. Both δ and the lag length were determined from Akaike Information Criteria (AIC) and the Schwartz Criteria (SC) test statistics, but fortunately the models are not sensitive to the choice of either δ or the lag length.[4]

For patents, a similar approach is not only justified but is entirely necessary. The difficulty with the raw patent data is that it gives

4. The $AIC_i = (MLL_i - k_i)$ and $SC_i = [MLL_i - 0.5k_i(\ln N)]$, where MLL_i is the maximized log-likelihood for model i, k_i is the number of parameters, and N is the sample size.

FIGURE 2
Foreign Patents in Germany



rise to a predominance of negative coefficients. The cause of this problem can be seen in Figure 2, which plots the patents registered in Germany, by foreign countries. The figure shows that *all* the foreign patent counts decline over the period, and this is true of the domestic patent series as well, which is not shown in the figure because the larger scale compresses the other series too much. The same is true of almost all the other patent series.

The literature (e.g., Griliches, 1990) suggests that the lower counts do not necessarily mean less technology transfer, but result from other measurement problems, which require further investigation. Segerström's (1998) endogenous growth model addresses some of the problems. Griliches (1984) noted the fall in patents in the 1970s and has commented in some detail on the difficulties of using time series patent data as economic indicators (Griliches, 1990). Using capital stocks rather than straight patent counts overcomes this problem. Thus, the PIM is again used to create technology capital stocks from all the patent series and the rate of depreciation is again set at 5%, since the persistence remains considerable (17 years in the United States, e.g.). The lags on education are shorter and are determined directly, without the formation of a stock variable.

The choice of model is complicated by the fact that the length of the PDL on R&D and the lags on the other variables need to be jointly determined. The F statistic and the log likelihood ratio were used, supplemented by the AIC and the SC, which were in agreement in almost all cases. These tests were used in combination with variable deletion tests, which indicated variables that could be jointly deleted from the equations.

V. ESTIMATION: PANEL MODELS, WITH AND WITHOUT PATENTS AND SPILLOVERS

Panel data estimation gives ample degrees of freedom, and both the cross sectional and time series variances help to determine the parameter estimates. The cost is in terms of imposing restrictions, and the fixed effects model assumes that the intercepts vary, but the slope coefficients are the same. This is equivalent to least squares with country-specific dummy variables (LSDV) as used here. Hausman (1978) tests and the Schwartz criterion were used in panel model selection.

The results of fitting equation (1) as a LSDV panel are reported in Table 2. In the closed economy model domestic patents and international spillovers of public and private R&D are not incorporated ("PDL no Private"). The lag structure applied to public R&D is a

TABLE 2
Results for LSDV Panel PDL and PIM Models

	Panel (with 200 observations)							
	Closed Economy				Open Economy			
	PDL no Private		PDL with Private		PDL		PIM	
Regressors	**Coeff.**	***t***	**Coeff.**	***t***	**Coeff.**	***t***	**Coeff.**	***t***
Constant	11.95	7.14	16.22	11.07	12.61	3.30	10.72	3.11
Own R&D	0.016	12.24	0.011	8.91	0.003	2.40		
Own R&D (–1)	0.028	12.24	0.019	8.91	0.005	2.40		
Own R&D (–2)	0.037	12.24	0.025	8.91	0.007	2.40		
Own R&D (–3)	0.044	12.24	0.030	8.91	0.008	2.40		
Own R&D (–4)	0.047	12.24	0.032	8.91	0.009	2.40		
Own R&D (–5)	0.047	12.24	0.032	8.91	0.009	2.40		
Own R&D (–6)	0.044	12.24	0.030	8.91	0.008	2.40		
Own R&D (–7)	0.037	12.24	0.025	8.91	0.007	2.40		
Own R&D (–8)	0.028	12.24	0.019	8.91	0.005	2.40		
Own R&D (–9)	0.016	12.24	0.011	8.91	0.003	2.40		
Σ sum Own R&D lags	0.342	12.24	0.232	8.91	0.063	2.40		
PIM R&D (–7)							0.110	3.53
Foreign R&D (–11)					0.280	3.17	0.200	2.24
Start value	–3.02	–6.90	–4.01	–10.58	–3.28	–3.47	–2.63	–3.18
Secondary education (–1)	0.365	8.20	0.192	4.63	0.092	2.11		
Land quality index	0.017	7.68	0.020	10.77	0.006	2.76	0.010	3.71
Own patents (–5, –12, –11)			0.102	9.24	0.133	2.66	0.074	3.07
Foreign patents (–5)					0.251	4.03	0.174	3.49
Patent Interact (–12)					–0.092	–3.05	–0.057	–3.98
Adjusted R^2	0.91		0.94		0.97		0.97	
F statistic	185.00		252.83		358.03		403.56	
Log likelihood	219.57		257.19		303.93		308.07	

t = t-statistic.

second-degree polynomial, with a 10-period lag.[5] There is no doubt that public R&D is highly significant even when the same structure has to be applied to all 10 countries. Secondary education is also highly significant, as is the land quality index. The closed economy model also establishes β convergence (Barro and Sala-i-Martin, 1995) conditional on public R&D, education, and land quality, by the significance of the starting value (1973) of TFP. In the open economy models, this result continues to hold, conditional on domestic and foreign patents as well as the other variables. The negative effect of the starting values indicates that less productive countries tend to catch up. Overall, 91% of the variance in TFP is explained in the closed economy model without the private sector, although, as we will show, the model is misspecified.

The next columns ("PDL with Private") report the results of fitting the same model with stocks of domestic patents included. This results in a substantial elasticity of 0.102 for domestic patents lagged 5 years in the closed economy model, but it is the sum of the public R&D elasticities of 0.232 that is crucial for comparison with the previous model, as this shows the distortion that results from ignoring the private sector. The public R&D elasticity is reduced by over 30%, the education elasticity by almost 50%, and the adjusted R^2 and the diagnostic statistics are all improved somewhat.

The spillover effects for the NARS expenditures and the foreign patent series are added in the PDL and PIM open economy models, reported in the next two sets of columns. The starting value and the elasticity for secondary education still have the expected signs and significance (in the PDL), and so does the land quality index. Domestic patents now must be lagged 12 and 11 years. The number of patents registered in any country by all the foreign countries has a large elasticity in both the PDL and PIM open economy models and is highly significant, which suggests that, in aggregate, foreign patents are more important than domestic patents, a result that is robust to alternative specifications of the domestic R&D stock, and the exclusion of secondary education.

5. Ten periods is not really adequate but is as far back as the available data allow.

The elasticities for the expenditures of the foreign NARS are large and significant in both the PDL and PIM open economy models. The significance of this variable and foreign patents in both models indicates that a failure to account for public and private spillovers could well explain why the returns to public R&D are often unbelievably high. The interaction of domestic and foreign patents is also significant in both of the open economy models. The open economy models including spillovers increase the explanatory power by 3% over the best closed economy model, and the diagnostic statistics are improved.

The negative sign on the interaction indicates that the smaller the contribution of foreign patents, the higher the level of domestic patenting, and vice versa. Table 3 presents the contribution to TFP of domestic and foreign patents individually, which include the interaction effects, evaluated at the minimum, maximum and mean of the relevant variables.

When the interaction term is taken into account, the uniformly positive effect on TFP of both domestic and foreign patenting activity in Table 2 no longer holds. In fact, it is only foreign patenting, when the smallest interaction effect from domestic patenting is included, that continues to show a positive impact on TFP. The reason is that domestic and foreign patenting both have quite strong negative effects on each other. These effects will be the subject of future research. Here, the signs obtained are robust to alternative specifications, with the elasticities obtained from the PIM open economy model being in all cases smaller than those obtained from the PDL.

VI. RATES OF RETURN TO R&D

The coefficients of the R&D variables (α_j), however they are estimated, are output elasticities relating R&D expenditures to the TFP index, but they can be converted to marginal value products to allow calculation of the marginal internal rate of return (MIRR) to R&D (Sveikauskas, 1986).

Table 4 shows how sensitive the MIRR calculations are to different formulations of the model. The calculation of the MIRR for the 10 EC countries together with the United States, from the pooled elasticity estimates reported in Table 2, shows that the closed economy model without domestic patents gives a rate of

TABLE 3
Elasticity of TFP to Private Sector Patenting including Interaction Effects (Domestic*Foreign)

Evaluated at	Open Economy Model	Domestic Patents	Foreign Patents
Minimum value	PDL	−0.204	0.086
	PIM	−0.135	0.072
Mean value	PDL	−0.574	−0.427
	PIM	−0.364	−0.246
Maximum value	PDL	−0.721	−0.726
	PIM	−0.455	−0.432

return of over 60%. This falls to less than 50% when domestic patents are included and is drastically reduced to 7.8% once spillovers are accounted for in the open economy model. While this is still a perfectly acceptable return, it is one eighth of the inflated return suggested by the first misspecified model. For this case, the additional return of 4.1% resulting from spillover effects should also be included, giving a total social rate of return of 12%, one fifth of the original inflated return. The PIM requires more complex calculations to generate an MIRR (see Khatri and Thirtle, 1996), and the result is still lower at 5.7% for domestic R&D, plus 3.7% for the spillover effects. Even this result suggests that the EC has some way to go before facing any danger of overinvesting in agricultural R&D, but the returns are far lower than for the closed economy model, even when spillovers are added to the open economy results. The importance of the spillovers may indicate that more collaboration between the EC research systems would reduce duplication and improve efficiency.

VII. SUMMARY AND CONCLUSIONS

This paper compares multilateral TFP indices for 10 EC countries and the United States. At the start of the period the EC was at 77% of the U.S. productivity level. But over the period, the U.S. growth rate was 3% while the 10 EC countries managed an annual average rate of only 1.92%. Thus, by the end of the period, the productivity gap had widened substantially, such that EC efficiency levels were only at two thirds of the U.S. level.

These aggregate figures hide an unexpected division of the EC countries into two groups. The high-technology countries are the Netherlands, Denmark, France, and Belgium, who converge with the United States at productivity levels between 130 and 150. These countries appear to have formed a club based on technological proximity, partly caused by knowledge and particularly by technological spill-overs, and are growing faster than the remainder of the EC. The group of laggards at lower productivity levels between 80 and 100 are Germany, Italy, Greece, Ireland, and the United Kingdom. The United Kingdom was a member of the high-technology club until the mid 1980s, when factors such as budget cuts drastically reduced its growth rate and the United Kingdom slipped into the second rank of the hierarchy. Thus, spillovers are a force in the direction of making the same technology available to all the countries, and they are partly responsible for the divergence detected graphically between the high- and low-technology clubs, because they expose the leaders to external increasing returns to scale. It may or may not be possible to separate out these effects in future research because of multicollinearity.

The changes in TFP are explained by public R&D, education, land quality, and private sector research, and by allowing for spillovers between research jurisdictions. Ignoring spillovers between countries gives misleading results, whereas including them improves the regressions, giving greater explanatory power and more robust estimates. Failing to include

TABLE 4
Marginal Internal Rates of Return to Public R&D, with and without Spillovers

	Panel with 210 Observations			
	Closed Economy		Open Economy	
	PDL no Private	PDL with Private	PDL	PIM
MIRR to domestic public R&D	64.5%	46.3%	7.8%	5.7%
MIRR to foreign public spillovers	–	–	4.1%	3.7%

Note: Direct private sector effects and foreign private sector spillover effects are estimated in Tables 2 and 3.

the spillovers biases the elasticities of R&D, so ignoring spillovers could be a major cause of the inflated estimates of the returns to investments in NARS that are often reported. The spillover variables appear to have greater explanatory power than such commonly used explanatory variables as extension and the weather, which contribute very little to explaining TFP growth for these European countries. The rate of return results suggest that, likewise, calculations of the returns to R&D at the national level may be misleading unless international flows of agricultural technology are taken into account. Thus, the return to public R&D falls from over 60% to 10–12% when the private sector and international spillovers are allowed for. The growth of collaborative EC research and the increasing role of multinationals will exacerbate this tendency for closed models to give biased results.

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